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EARTHQUAKE SAFETY PROGRAM
AT
LAWRENCE LIVERMORE NATIONAL LABORATORY

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DISCLAIMER

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ABSTRACT

Within three minutes on the morning of January 24, 1980, an earthquake and three aftershocks, with Richter magnitudes of 5.8, 5.1, 4.0, and 4.2, respectively, struck the Livermore Valley. Two days later, a Richter magnitude 5.4 earthquake occurred, which had its epicenter about 4 miles northwest of the Lawrence Livermore National Laboratory (LLNL).

Although no one at the Lab was seriously injured, these earthquakes caused considerable damage and disruption. Masonry and concrete structures cracked and broke, trailers shifted and fell off their pedestals, office ceilings and overhead lighting fell, and bookcases overturned. We suddenly found ourselves immersed in a site-wide program of repairing earthquake-damaged facilities, and protecting our many employees and the surrounding community from future earthquakes. Over the past five years, LLNL has spent approximately $10 million on its earthquake restoration effort for repairs and upgrades.

The discussion in this paper centers upon the earthquake damage that occurred, our clean-up and restoration efforts, the seismic review of LLNL facilities, our site-specific seismic design criteria, computer-floor upgrades, ceiling-system upgrades, unique building seismic upgrades, geologic and seismologic studies, and seismic instrumentation.

INTRODUCTION

Lawrence Livermore National Laboratory (LLNL), originally the site of a U.S. Naval Training Station, was established in 1952. It is operated by the University of California for the U.S. Department of Energy, and is located in the Livermore valley about 40 miles east of San Francisco and Oakland California, in one of the world's most seismically active regions. Because of the earthquake hazard, LLNL has combined its technical understanding of the problem along with its expertise in the field of earthquake engineering (geology, seismology, and nuclear and non-nuclear facility design) to become one of the most seismically resistant industrial complexes in the world.

The Laboratory's Livermore site is approximately one square mile (640 acres) in size and contains municipal services that are similar to those normally found in any small city: police and fire departments, a medical department, and water/sewer/electrical/natural gas distribution systems. Presently, the personnel at the site number around 8,000, with an increase in population expected in the years to come. There are 174 buildings that enclose about 3,400,000 sq. ft (gross) of floor space, and over 1,000 trailers. The Laboratory's annual budget is approximately $700,000,000; its facilities (excluding utilities and the contents of buildings) are estimated as being worth about 750,000,000 1985 dollars. The primary mission of the Laboratory is the design of nuclear weapons; other programs include laser fusion, laser isotope separation, magnetic fusion, non-nuclear energy technologies, and biomedical and environmental studies.

SEISMIC SETTING OF THE LABORATORY

Besides being in the seismically active Livermore Valley, LLNL is located between two extensive fault systems. To the east lies the Greenville-Tesla-Ortigalita Fault zone and to the west lies the Calaveras Fault zone, a branch of the San Andreas Fault zone. The Hayward Fault zone, another branch of the San Andreas, and the main part of the San Andreas itself, lie still farther west. All of these faults are in the coastal region of central California, one of the most seismically active regions in the United States.

THE 1980 LIVERMORE EARTHQUAKE

At 11:00 a.m. on Thursday, January 24, 1980, we at LLNL experienced an earthquake with a Richter magnitude of 5.8. Three relatively large aftershocks with magnitudes of 5.1, 4.0, and 4.2 followed within three minutes. On January 26th, an earthquake with a Richter magnitude of 5.4 occurred. The epicenter of the January 24th event was about 13 miles northwest of the Laboratory; the

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epicenter of the January 26th event was about 4 miles northwest of the Lab. Peak ground accelerations of 0.17g were recorded at the Livermore Veterans Administration Hospital (5 miles southwest of LLNL), 0.21 to 0.26g at the Del Valle Dam (6 miles southeast of LLNL), and 0.11g at General Electric's Vallecitos nuclear-reactor site (10 miles southwest of LLNL). The peak ground accelerations at LLNL were estimated as having been in the range of from 0.2 to 0.3g, with the major seismic component being in the East-West direction. There were no strong-motion earthquake instruments at LLNL during the earthquake: this lack was soon rectified. (The Livermore earthquake, a seismic event of moderate-size, is considered small compared to the roughly 8.6 magnitude San Francisco earthquake of 1906.)

DAMAGE RESPONSE TEAMS

Within an hour after the January 24, 1980, main event, structural, mechanical, and electrical damage-response teams had been formed and were in the field. These teams were responsible for evaluating the damage to, and the condition of, the Laboratory's buildings, trailers, and utility systems, and for formulating recommendations to Laboratory management. Three structural investigation teams were assembled.

Engineering consulting firms were hired to address concerns raised by the structural investigation teams as to whether Building 113, a seven-story computer office building, and Building 311, a two-story office building, could still be safely occupied.

EARTHQUAKE DAMAGE AT THE LABORATORY

Although no one was seriously injured, the Livermore earthquake caused considerable damage and disruption at the Laboratory. Building walls of concrete and masonry were cracked and broken. Extensive cracking occurred in concrete structures throughout the laboratory. Much of the concrete cracking was considered as not being an immediate threat to the structural integrity of the buildings or structures. Building 311, a two-story concrete-frame office building housing the Plant Engineering and Personnel Departments, suffered considerable column damage at the juncture of the second floor and roof lines, equipment shifted from mounting pads, and staircases cracked. Building 113, the Laboratory's seven-story computer office building, suffered extensive cracking to its central lateral-force-resisting concrete core.

In other buildings, some connections between tilt-up concrete walls and their supporting structural-steel frames had failed. A few structural-steel welds failed, several loose or stretched bolts were noted, and damage to the connections of structural members was found throughout the site. A few structural-steel framing members had buckled in some of the buildings. Many elevators in the Laboratory's buildings could not be used because their counterweights had been knocked loose from their mounting brackets, bending the guide rails. Surprisingly, the Laboratory's facilities had very little window glass breakage. However, the concrete anchors used to fasten down various types of equipment and tanks were twisted or torn and, in some cases, were completely pulled out of the concrete.

Trailer support stands moved and toppled over on January 24th. Many trailers shifted, causing their outside doors to jam or be blocked, so that they could not be immediately opened.

Chemical containers in many chemistry laboratories were thrown from their storage shelves, to break and form mixed pools of chemical brew on the floors. Ceiling and light fixture failures were commonplace. In one of the laser engineering office buildings, a majority of the ceilings, overhead light fixtures, and air diffusers fell to the floor. Amazingly, no one was struck or injured. Overturned office furniture, such as bookcases, storage shelves, and filing cabinets, was commonplace. Papers were scattered everywhere. Sheetrock partitions were cracked. Broken water pipes caused water damage in several locations. Many of the main library's book stacks collapsed. Mainframe computer damage was minimal, although there was an increase in computer down-time after the earthquake; significant damage did occur to some minicomputers. The Lab's laser and test accelerator facilities experienced alignment problems with their systems.

Considering the size of the Laboratory's utility systems, very little damage occurred. Fuses on switches opened, causing circuit breakers to trip, resulting in a loss of power to most of the site for a short time. This shut down the main computers, which inactivated security booths and impeded access to some areas. The laboratory's emergency generators functioned normally during this period, and power was completely restored by the same afternoon. There were only minor breaks in the water system, and the main water supply to the laboratory was not damaged. Water for fire fighting was available at all times. Water leaks occurred in some of the mains and in some of the building systems, including fire sprinkler systems. A few natural gas leaks occurred in the mains and the building systems. The Laboratory's emergency supply of natural gas, three 30,000 gallon propane tanks, was not needed and was not damaged.

Other than minor disruptions, no damage was done to any of the buildings and structures (including their associated safety systems) housing LLNL's nuclear materials. They performed as expected.

The Medical Department received 35

patients immediately after the earthquake with lacerations, sprains, bruises, back problems, and other minor conditions. No one required an ambulance transfer. During the following weeks, 30 more people reported injuries that were apparently related to the earthquake. Of these injuries, 46 were caused by falls or falling objects.

The January 1980 earthquake and aftershocks gave the Laboratory a first-hand opportunity, on a small scale, to observe the damage, disruption, and emotional and physical pain that "Mother Nature" can cause. Although the earthquakes were moderate in size, the damage done nonetheless provided a test for the Lab, and gave both the Lab population and its management an awareness about the nature of their environment that they may not have had before.

EARTHQUAKE CLEAN-UP AND RESTORATION EFFORTS

The immediate task at hand was to put the Laboratory's damaged facilities back together and restore normal composure. Safety issues, intertwined with the immediate possibility of further ground shaking were paramount in everyone's thoughts. The Laboratory had to act quickly. The problem fell to the Plant Engineering Department, which began by forming a Structural Engineering Group. This technically strong and discipline-oriented group was needed to address earthquake-related issues, while also performing Plant Engineering's more traditional role of supplying structural design support to major laboratory projects.

Much of the damage and disarray was found to be primarily of an architectural and cosmetic nature. Laboratory personnel were allowed to re-occupy Buildings 311 and 113 during the remedial crack repair. To various degrees, the majority of the Laboratory's concrete buildings and structures experienced concrete cracking. Although they were considered as safe for continued occupation, the cracks were still repaired by epoxy injection. There were several reasons for doing this. The quality of a building's external appearance is always important - psychologically, the occupants are often concerned about their safety whenever even a small amount of concrete cracking occurs. Also, over the long term, a concrete structure should be watertight, so as to protect the reinforcing steel.

Plant Engineering craftspersons (laborers, carpenters, electricians, and painters) assisted by the Hazard Control Department began the process of cleaning up. Natural gas was shut off as a precaution and restored as soon as the distribution systems were found to be safe. Water systems were repaired; debris was hauled away; offices, labs, and shop spaces were cleaned up, and building interiors were repaired and repainted. The various Departments and Programs within the Lab initiated the anchoring of bookcases and other office and lab equipment, and ceiling repairs and upgrades were begun. As a precautionary measure, staircases in several buildings were shored up, or roped off, until they could be thoroughly inspected. All building elevators and laboratory cranes were shut down until it could be determined that they were safe to operate. Short- and long-term programs were begun to repair and upgrade the Lab's facilities. A detailed discussion of the earthquake-related damage, and its effect on the Laboratory, appears in Reference 1.

EARTHQUAKE CLEAN-UP AND RESTORATION EXPENDITURES

From 1981 to 1985, LLNL spent approximately $10,000,000 on the earthquake restoration, repair, and upgrade effort. These expenditures are broken down as follows: for FY 1981 (Non-Capital Monies) $4,167,000, for FY 1981/1982 (Capital Monies) $4,000,000, and for FY 1983/1984 (Capital Monies) $1,350,000.

INDEPENDENT SEISMIC REVIEW OF LLNL FACILITIES

In order to satisfy ourselves that the immediate course of action being taken by the Laboratory was correct (with respect to the planned facility upgrades and personnel seismic-safety issues), we engaged an outside, independent, structural engineering firm specializing in seismic hazard abatement. They were initially asked to review 27 of the Lab's older buildings and structures, housing the majority of the Lab's personnel, to determine their adequacy for resisting earthquakes (with respect to their occupants' safety). The methodology used in the review was that prescribed by the University of California Facilities Manual, Sect. B-3.2, "Seismic Safety Policy."[2] The consulting structural engineer was required to express his opinion as to the structure's anticipated seismic performance (Good, Fair, Poor, or Very Poor, which is quoted from the Facilities Manual) with respect to the risk of injury to persons in a major seismic disturbance. For the purposes of these seismic performance ratings, a "major seismic disturbance" was defined as an earthquake at the site with a Modified Mercalli Intensity Scale rating of at least IX (based on a description of the structural effects).

The consulting firm was then asked to review all of LLNL's facilities within the Livermore Valley, approximately 241 buildings and structures, and to list their Benefit to Cost Ratios (BCRs) in descending order. The BCR is an estimate of the lives postulated as being saved per reconstruction dollar. The trailers at the Laboratory site were excluded from this study. The BCR method provides a relatively quick, low-cost method of evaluating the relative seismic hazard of a large number of buildings with diverse types of construction. The methodology used was that prescribed by the State of California Seismic Safety Commission Report, Evaluating the Seismic Hazard of State Owned Buildings, Sect. 79-01.[3] The Benefit to Cost Ratios are used as one of several management tools for generating priorities for further study or reconstruction.

The independent seismic reviews of LLNL's facilities, together with the Lab's own data, gave us a very good idea of just what seismic rehabilitation was needed. Of all the laboratory's buildings, only Building 311 was in the Very Poor or Poor category. Two additional structures, an outside seven-story stair tower adjacent to Building 111 and a vault area in Building 261, were also in the Very Poor or Poor categories with respect to their seismic ratings. Building 311 and the seven-story stair tower have been structurally upgraded. They now have seismic ratings of Good and Fair, respectively. The vault has been torn down. Building 113, which was rated as Fair before its structural upgrade, is now rated as Good.

SITE-SPECIFIC SEISMIC DESIGN CRITERIA FOR LLNL FACILITIES

Since 1980, LLNL's Hazardous Facilities have been designed and evaluated using state-of-the-art earthquake engineering methods and site-specific geologic and seismologic data. This design policy will not change in the future. Conventional buildings, however, were constructed using standard engineering design methods, in conjunction with the minimum building code requirements established by the building industry. After the 1980 earthquakes, the Laboratory began an immediate review and evaluation of the earthquake design criteria being used for its non-nuclear conventional facilities. A significant difference exists between today's seismic building codes for new construction and the building codes of the 1950s and 60s. For example, the 1961 Uniform Building Code (UBC) would require that a building at LLNL be designed to resist a lateral force equal to 0.067 of its total weight, W, but the 1982 edition of the UBC would require the same building to be designed to resist 0.094W. Building code standards often do not take into account the uniqueness of a particular site or situation, and should therefore only be considered as representing minimum requirements. Taking into account data for the site-specific probability of earthquake occurrences, the site-specific earthquake response data, safety considerations for Laboratory personnel, and programmatic requirements with regard to the benefit received vs the dollars expended, LLNL chose to write its own earthquake design criteria for its conventional buildings and structures. Studies are continuously being made as part of an on-going process to re-evaluate and improve LLNL's site-specific technical data. The minimum seismic design requirements for LLNL's new buildings and structures, as of this writing, are quoted in the following section.

LLNL SEISMIC CRITERIA FOR FACILITIES

1. OPERABILITY

A) The Laboratory's buildings, structures, systems, and components shall be categorized and listed in one of the four LLNL safety classifications: High Hazard, Moderate Hazard, Low Hazard, and No Hazard (Conventional Building) status. Guidelines for classification shall be provided by LLNL's Hazard Control Department. Each safety classification has its own design basis earthquake (DBE) excitation criteria.

B) Hazard and Non-Hazard structures, systems, and components shall include, but not be limited to, building structure, piping, electrical conduit, mechanical systems, electrical systems, associated support systems, etc.

C) High Hazard and Moderate Hazard categories shall each be sub-divided into two sub-classifications — Seismic Category I items and Non-Seismic Category I items.

D) <u>Seismic Category I</u> structures, systems, and components are those items whose <u>continued integrity</u> and/or <u>operability</u> are <u>essential</u> to assure the capability to shut down and maintain a <u>safe shutdown</u> condition, and to prevent or <u>mitigate the consequences</u> of accidents which could result in potential off-site exposures.

E) A thorough structural analysis and design or testing program is to be accomplished to ensure that the <u>integrity</u> and <u>operability</u> of the Seismic Category I structures, systems, and components will be maintained for the Design Basis Earthquake (DBE) Conditions. Seismic Category I structures, systems, and components shall be designed to remain <u>functional</u> during and after the Design Basis Earthquake.

F) Evaluation of Non-Seismic Category I items (structures, systems, and components) shall be made on a case-by-case basis. Non-Seismic Category I items shall be designed using LLNL's No Hazard, Standard Facility Criteria. Failure of Non-Category I items and Category I items must not cause failure of any Category I items with respect to the successive higher levels of DBE requirements. An item in a lower Safety Classification must not cause failure of an item in a higher Safety Classification.

G) The latest edition of the Mechanical Engineering Department's "Design Safety Standards" (LLNL Manual M-012) should be consulted with respect to possible guidance for the anchoring of programmatic equipment.

2. SEISMIC EXCITATION

A) The Design Basis Earthquake (DBE) input ground motion to a given structure, system, or component configuration is uniquely defined by the specification of the horizontal peak ground acceleration (PGA) and the LLNL DBE horizontal Ground Response Spectra. The vertical peak ground acceleration is two-thirds of the horizontal peak ground acceleration. The response values of the <u>vertical</u> ground response spectra are equal to <u>two-thirds</u> (2/3) of the response values for the <u>horizontal</u> ground response spectra.

B) The DBE horizontal ground motion shall be assumed to occur in any orientation within the horizontal ground motion plane for the given structure. The horizontal ground motion shall be considered to act simultaneously with the vertical ground motion (two-directional excitations).

C) <u>High Hazard Seismic Excitation and Design Requirements</u> LLNL High Hazard structures, systems, and components (Seismic Category I items) must go through a two-step design process. The first process consists of evaluation and design in the elastic range of response. It is done using a dynamic response spectral analysis with the LLNL Ground Response Spectra and a corresponding horizontal peak ground acceleration (PGA) of 0.50g (DBE) applied simultaneously with a vertical PGA of ± 0.333g. Engineering evaluations and design shall be accomplished by using UBC analysis methods along with UBC Strength Allowables. Connection evaluation and design shall account for an additional load factor of 1.5, that is, the connection design/evaluation uses forces which are 1.5 times those due to the 0.50g DBE (horizontal + vertical). The second part of the design process takes the components into the inelastic range and checks the integrity of the Seismic Category I items against forces due to a Design Basis Earthquake with a horizontal PGA of 0.80g applied simultaneously with a vertical PGA of ± 0.533g. For this check, the item must remain functional during and after the earthquake.

D) <u>Moderate Hazard Seismic Excitation and Design Requirements</u> LLNL Moderate Hazard structures, systems, and components (Seismic Category I items) must go through a two-step design process. The first process consists of evaluation and design in the elastic range of response. It is done using a dynamic response spectral analysis with the LLNL Ground Response Spectra and a corresponding horizontal peak ground acceleration (PGA) of 0.25g DBE applied simultaneously with a vertical PGA of ± 0.17g. Engineering evaluations and design shall be accomplished by using UBC analysis methods along with UBC Strength Allowables. Connection evaluation and design shall account for an additional load factor of 1.5, that is the connection design/evaluation uses forces which are 1.5 times those due to the 0.25g DBE (horizontal + vertical). The second part of the design process takes the components into the inelastic range and checks the integrity of the Seismic Category I items against forces due to a Design Basis Earthquake with a horizontal PGA of 0.50g applied simultaneously with a vertical PGA of ± 0.333g. For this check, the item must remain functional during and after the earthquake.

E) <u>Low Hazard and No Hazard (Conventional Buildings) Seismic Excitation and Design Requirements</u>

1) <u>One and Two-Story Buildings and Structures</u> Current Uniform Building Code (UBC) requirements upgraded for a building seismic lateral load coefficient of 0.25W (static). If UBC seismic requirements are more severe, UBC seismic requirements shall control. Connection evaluation and design, due to seismic forces, shall account for an additional load factor of 1.5; i.e., Connection Design/Evaluation Loads = 1.5 by 0.25W Loads. This will help to assure that the building's structural elements can reach their maximum potential for ductility.

Analysis procedures, design procedures, and material strength allowables shall meet the requirements of the latest edition of the <u>Uniform Building Code</u>[4] and DOE 6430.1, <u>Facilities General Design Criteria</u>.[5] Lateral forces used in the design and evaluation of structural and non-structural components shall meet the basic performance requirements of the Uniform Building Code.

2) Buildings and Structures Greater Than Two Stories Buildings and structures over two stories in height shall meet the seismic design requirements for One and Two-Story Buildings and Structures.

Buildings and structures over two stories in height shall also be evaluated and designed using the LLNL Ground Response Spectra with a corresponding horizontal peak ground acceleration (PGA) of 0.50g applied simulataneously with a vertical PGA of $\pm$ 0.333g.

Engineering evaluations and design shall be accomplished by the use of inelastic analysis methods combined with inelastic stress allowables. Little regard shall be given to the condition of the building following the 0.50g DBE. Primary concern is to ensure prevention of building collapse, thereby allowing the building occupants to egress safely following an earthquake having major intensity at the site.

Lateral forces used in the design and evaluation of structural and non-structural components shall meet the basic performance requirements of the building structure.

3) All Buildings and Structures with Significant Cross Axes Coupling and/or Torsional Response The design of buildings and structures placed within this category shall meet the requirements of "2)" (above).

LLNL's COMPUTER FACILITIES

Lawrence Livermore National Laboratory is the home of many millions of dollars worth of computer equipment. Much of this equipment sits on a type of suspended flooring known as a "computer floor." Although little damage occurred to the Lab's computational facilities during the January 1980 earthquake and aftershocks, concern was focused in this area by asking, "If a larger seismic event were to occur, what would happen to the Lab's computers?" Since then, we have been reassessing the structural aspects of the existing computer floors and their ability to resist earthquake-induced forces. If computer flooring is found to be deficient, repairs are made. Seismic switches have been installed that will turn off electrical power to the Lab's main computers in the event of a large earthquake.

Computer floors typically consist of vertical supports, called pedestals. Diagonal bracing of pedestals is often discouraged, since it could obstruct the passage of electrical conduits, piping, and ducting beneath the raised floor. Pedestals that are not laterally supported by diagonal bracing will have to resist seismic forces by the bending action of the pedestal tube.

The Laboratory has prepared new standards, specifications, and drawings encompassing the design aspects of seismic criteria for conventional computer floors. All raised-floor or computer-floor suppliers and vendors are required either to use the Lab's standard drawing for pedestal assemblies, or to demonstrate by tests or calculations that their pedestals and floor panels can meet the Lab's computer-floor criteria.

LLNL's SEISMIC CRITERIA FOR COMPUTER FLOORS

The following forces are to be used for designing LLNL's computer floors:

- Dead Load (D.L.) = 9 pounds per square foot (psf*)
- Live Load (L.L.) = 250 psf*
- Horizontal Seismic Force (H) = $\pm$ 0.5 (DL + LL/4)
- Vertical Seismic Force (V) = $\pm$ 0.333 (DL + LL/4)

The horizontal and vertical seismic forces are assumed to act concurrently. Design allowables from the UBC are to be used for computer floor designs. The pedestal base plates must be positively connected to the floor by bolts or power-driven fasteners. Design calculations are to be provided by a registered California Civil or Structural Engineer.

* Large equipment items must be checked on a per-item basis.

GEOLOGIC AND SEISMOLOGIC STUDIES AT THE LIVERMORE SITE

Since early 1979, geoscience personnel in LLNL's K Division have been engaged in comprehensive geologic and seismologic studies of the Lab's Livermore site and the surrounding area. These on-going studies evaluate potential geologic hazards (such as earthquakes), which could affect the safety of operations at the Laboratory. These studies are also used as a check on the Lab's seismic design criteria. To date, the only significant seismic hazards that have been identified appear to be those associated with strong ground motion resulting from faults located some distance from the Laboratory. It has been found that surface rupture is very unlikely, since no active faults cross the Livermore site and the Laboratory islocated on top of a deep alluvial fill. Geophysical exploration, trenching, and drilling have shown that the substrata under the Lab consist of 300,000 to 500,000 year old continuous sedimentary layers, as much as 4000 ft thick,[6,7] without fault offsets.

In conjunction with the U.S. Geological Survey, the Lab has established a local network of highly sensitive seismometers that record the components of small- to micro-size earthquake ground motions in the Livermore Valley. Monitoring microquakes will help to delineate zones of earthquake activity, and to determine what the ambient seismicity levels are in the Livermore Valley.

SEISMIC INSTRUMENTATION

There were no strong-motion earthquake instruments at LLNL during the January 1980 earthquake. However, accelerations of 0.17g and 0.26g were recorded by accelerographs located at the nearby Veterans Hospital and Del Valle Dam, respectively. In a very short time (through the efforts of Mechanical Engineering's Structural Mechanics Group) strong-motion monitoring and recording accelerographs (seismometers) were installed at the Lab as part of the earthquake safety program. The network includes digital multi-channel central recording systems, with independent analog accelerographs providing redundancy.

The Laboratory's strong-motion seismometers will help in assessing the impact of the geology under and near the Lab, with respect to any localized amplification of ground shaking. The network will also provide a rapid indication of peak ground-motion values, and data for detailed post-earthquake studies of ground motions and structural responses.

At the present time, LLNL has installed six free-field, 1-g, self-contained, digital seismometers on or near the Laboratory. Each seismometer can record accelerations in three orthogonal directions.

Building 111 (a complex seven-story unsymmetric high-rise structure) and Building 332 have both had strong-motion seismometers installed in them. Seismometers have also been mounted on the laser program's large spaceframe. Sandia Livermore Laboratory, which abuts LLNL just to the south, has also placed seismometers in its tritium facility, Building 981. These instruments will provide rapid indications of the buildings' earthquake response, and will help us to assess any possible structural effects.

Detailed discussions of the strong-motion instrumentation program can be found in Reference 8.

SEISMIC UPGRADES OF EQUIPMENT AND STRUCTURES

OFFICE EQUIPMENT AND LIBRARY SHELVING

After the January 1980 Livermore earthquake, the Lab immediately instituted a program of tying down office equipment and major shelving, such as file drawers, cabinets, and bookcases. Guidelines for anchoring office equipment were written, and the required earthquake performance criteria for major library shelving were defined. All bookcases taller than four feet must be anchored. New library shelving was designed to withstand an applied earthquake force of 0.50W without collapsing.

Outside contractors were then brought into the Lab to anchor office equipment, one building at a time.

MECHANICAL AND ELECTRICAL EQUIPMENT

Most mechanical and electrical equipment items that had been properly tied down sustained little damage. Those items which were not anchored moved, shifted, or (in some cases) overturned. Revised guidelines for anchoring programmatic equipment were issued by the Mechanical Engineering Department (the Design Safety Standards Manual, M102). When items were found deficient, steps were taken to properly anchor them.

TRAILERS

Acute space shortages have led LLNL to use trailers for filling its housing needs. Before the January 1980 earthquakes, many of these trailers were not anchored well enough to resist earthquake forces. Since then, all newly acquired trailers must be designed to resist concurrent horizontal and vertical earthquake forces of 0.25W and 0.167W, respectively, while meeting UBC design requirements. All existing (new and old) trailers at the Lab must be able to resist the effects of earthquake motion without falling or overturning. Support systems that will safely allow sliding, or piers and soil anchors, or perimeter foundations with anchors, must now be used to meet these requirements.

CEILINGS AND LIGHT FIXTURES

After the earthquake, ceilings and light fixtures at LLNL are either being upgraded to the standards of the latest edition (at the time of the effort) of the Uniform Building Code Standard No. 47-19, Metal Suspension Systems for Acoustical Tile and for Lay-In Panel Ceilings, or are being designed, as new, to meet the standards from this same source. In addition, a ceiling system must be designed (or upgraded) with vertical struts that are able to resist vertical seismic forces acting in both the up and down directions. Plastic lenses used with ceiling lights, and bare fluorescent tubes, must also be secured from possible falls.

BRIDGE CRANES

There were no cases of trolley or bridge assemblies jumping their rails during the January 1980 earthquake. Nevertheless, the Lab is installing mechanical restraints on approximately 54 bridge cranes to prevent this from happening due to future earthquake-induced motion.

PROPANE TANKS

Rigid connections between tanks and piping headers are vulnerable to rupture, since the tanks and piping systems are independently anchored. Any significant differential movement during seismic activity could result in piping breaks near the tank end of the connections. Although there were no problems with the propane tanks during the January 1980 earthquakes, flexible piping connections are being added to prevent such potential piping failures.

SEISMICALLY ACTIVATED GAS SHUTOFF VALVES

Gas shutoff valves are being installed at the Laboratory to help mitigate the potential for fires or explosions, which could result from leaking or ruptured gas supply lines. These valves are automatically closed by earthquake motion.

SEISMIC UPGRADES OF MAJOR LABORATORY BUILDINGS AND STRUCTURES

SEISMIC UPGRADE OF BUILDING 311

Building 311, originally designed under the requirements of the 1961 Uniform Building Code (UBC) and constructed during 1964, suffered due to the January 1980 earthquake, considerable structural damage: vertical column splitting, concrete cracking, and cracking at the beam/column joints.

Building 311 is a reinforced-concrete structure with 37,000 ft^2 of gross floor space. It is about 95 by 190 ft in plan, and consists of two levels plus a penthouse. The typical bay size is 23 ft 9 in. square. The primary system used to resist lateral forces is a "moment-resisting frame" mounted on drilled piers. The first floor is a slab-on-grade, and the second floor and roof are framed with concrete beams and girders and infilled with pan joists. The building's columns are made of reinforced concrete.

Building 311 was intended to resist lateral wind or earthquake forces through action as a "moment-resisting frame," which is developed by the combined action of its beams and columns. The original design provided for resisting a lateral force of 0.067W, where W is the weight of the building. The 1982 edition of the UBC would require the same structure to resist a statically applied lateral force of 0.094W.

After the earthquake, the Lab decided to upgrade the seismic performance of Building 311. Structural Criteria for the building upgrade was written encompassing the Lab's previously discussed earthquake standards for one and two-story buildings.

The upgraded building was then checked, using site-specific ground response spectra, for its ability to survive without collapsing during an earthquake with a 0.50g peak ground acceleration.

The structural-upgrade solution was to construct and attach a series of external concrete shear walls (buttresses) to three of the four sides of Building 311; two on the west end, two on the east end, four on the south side, and none on the north side. The concrete buttresses were anchored to the ground by 3-ft diameter by 40-ft long drilled concrete piers, four piers per buttress. The buttresses were attached to the second-floor level of the building by rebar welded to steel-channel drag struts. These struts were, in turn, attached to the underside of the second-floor concrete beams by a series of specially designed steel bolts. The concrete buttresses were also attached to the concrete roof slab with rebar welded to steel-plate drag struts, which were attached by shear connectors to the top of the roof beams.

The structural-upgrade costs for Building 311 were approximately \$1,500,000 (in 1982 dollars) Replacing the building would have cost approximately \$4,600,000 (in 1982 dollars). The construction time for the structural portion of the upgrade took about 10 months. A detailed description of the Building 311 upgrade can be found in Reference 9.

SEISMIC UPGRADE OF BUILDING 113

Building 113 was designed in 1964 to meet the requirements of the 1961 Uniform Building Code (UBC). The main part of Building 113, the computation and office building, is a five-story reinforced-concrete structure, approximately 90 ft. square in plan dimensions, (3 bays by 3 bays), containing about 42,000 ft^2 of office space. It has a partial basement and a 14-ft high steel-frame penthouse located on the roof. Each of the 5 stories is 13-ft high, and the basement floor is 17 ft below the first floor level. The basement forms a passageway to the adjoining computer center. The structure is formed on 24-in. diameter cast-in-place reinforced-concrete piles.

The building has waffle slabs supported on columns, spaced on 30-ft centers each way, and a core of shear walls is located in the west half of the structure. The shear walls enclose two stair wells and elevator shafts, and are arranged so that the center of their rigidity falls close to the geometric center of the building. They were originally designed to carry about 80% of the lateral load, with the remaining 20% being resisted by the bending action of the building columns.

The original building design provided for a lateral force of 0.057 of the weight, W, of the building. The 1982 edition of the UBC would have required Building 113 to resist a statically applied lateral earthquake force of 0.14W.

The January 1980 earthquake caused no damage to the building's columns, the structural damage being confined to the central-core shear walls. They developed extensive diagonal tension cracking and sliding shear cracking along horizontal construction joints, which also showed signs of grinding or spalling. Cracking occurred throughout the building, but was more extensive in the lower stories. High-strength epoxy grout was injected into the core-wall cracks, repairing them in the same manner as was done for Building 311.

By February, 1981, the initial engineering effort was begun, both to structurally upgrade Building 113 and to increase its earthquake resistance. The structural design criteria specifically requested that the following steps be taken:

- Building 113 shall be upgraded, using LLNL's design response spectra, to resist a 0.5g horizontal peak acceleration earthquake; building collapse shall not occur.
- Extensive damage at this earthquake level is acceptable, provided that people can safely exit the building.
- The new structural elements required for preventing the collapse of the building at 0.5g shall meet the design requirements of the current UBC except for connections, which shall use an additional factor of 1.5.

Many different schemes for upgrading the building's structure were investigated. In the end, by considering such factors as cost, aesthetics, and impact and disruption as being equal, it was decided that the best approach was to keep the majority of the new construction on the outside. This allowed the building to remain occupied during the reconstruction.

The existing foundation pile system was considered to adequately meet the seismic criteria for the upgrade. Therefore, the upgrade scheme that was finally decided upon used steel "K" braced frames attached both to the outside face of the building perimeter and to the existing foundation system. These "K" frames were made of high-strength steel rectangular tubular sections, with 3/4-in. diameter Nelson stud anchors welded to their backs. The outside edges of the building's concrete floor and roof slabs were chipped back to expose the reinforcing bars. The "K" frames were installed along the outside perimeter of the building by attaching the Nelson studs to the building-slab edges with high-strength concrete grout. The "K" frames were attached to each other with welded steel plates, and to the existing foundation system by constructing new concrete grade beams. "K" frames were placed in all of the first and second story outside building bays, but only in the outside middle bays of the third, fourth, and fifth stories, thus forming an inverted "T" configuration at each building face.

The new building frames were designed to safely resist all of the seismic forces acting on Building 113 as a result of a major earthquake. The cost of the structural upgrade was approximately $1,100,000 (in 1982 dollars). It is estimated that replacing the building would have cost about $5,900,000 (in 1982 dollars). The construction time needed for doing the structural portion of the upgrade was about nine months.

SEISMIC UPGRADE OF BUILDING 111'S OUTSIDE STAIR TOWER

A seven-story reinforced-concrete stair tower, used for emergency egress, is adjacent to the south side of Building 111. Originally designed to behave as an independent, free-standing, cantilever beam when subjected to wind and earthquake forces, it swayed up to 3 in. in the north-south direction during the January, 1980 earthquake. As a result, it struck Building 111's stair landings, causing minor damage. The independent seismic review rated the stair tower as "Poor". Because of this, and the continuing need for the stair tower, it was decided to initiate a structural upgrade.

The stair tower is now laterally supported at each floor level and at the roof by structural-steel tube connections to Building 111. High-strength steel bolts were used to connect the tubes to the stair tower. Cinch anchors and grouted steel bolts connect the tubes to Building 111's peripheral beams and columns. The new steel tubing was then painted to match the existing building color. In this way, the stair tower was structurally upgraded to meet the earthquake design requirements of the 1982 UBC, and now has a "Fair" rating.

BUILDING 332 LOFT UPGRADE

As previously stated, no damage resulted from the January, 1980 earthquake to any of the buildings and structures housing LLNL's nuclear materials. These facilities performed as expected. Even so, the Laboratory is continually reviewing and upgrading these facilities. In 1981, it was decided to reinitiate an equipment tie-down program in Building 332, while structurally upgrading, if needed, the building's Loft area. A steel-framed structure with concrete precast walls and a metal roof deck, the Loft is essentially the second story of a two-story building. The Loft was reviewed and upgraded to satisfactorily resist the seismic forces resulting from a 0.8g Design

Basis Earthquake.

EMERGENCY PREPAREDNESS

An Emergency Operations Center has been created at the Laboratory to coordinate emergency activities, and to centralize management control and emergency communications during an emergency. This new center is being equipped to handle Lab communications after disasters such as major earthquakes.

At the time of the January, 1980 earthquake, the Lab did not have such an officially designated Emergency Operations Center. No single location was equipped to handle this kind of a site-wide emergency. The Lab's Centrex Telephone System became overloaded in the first few minutes: telephones in the emergency Fire, Security, and Plant Engineering centers were essentially unavailable because of the large number of incoming calls.

Most of the Lab's emergency communications after the earthquake ended up on only three radio frequencies. Ironically, all the Lab personnel's individual emergency radio pagers failed to work after the earthquake, because the relay transmitter had tipped over and become disconnected from its power source.

Initial assistance during Laboratory emergencies originates with the Hazards Control Department, through its Fire Department and safety teams assigned to different areas of the site. Besides training these emergency personnel in post-earthquake procedures, the Lab has included a chapter on earthquakes in its Health and Safety Manual (LLNL Manual M010) for employee use. The Hazards Control Department has also conducted many one-hour seminars on earthquake safety. The Lab's Disaster Control Plan (LLNL Manual M014) describes the duties of personnel, and methods for mobilizing them in emergencies. In addition, it has many supplements that give detailed guidance on special procedures that may be needed when a large-scale emergency occurs.

Since the earthquake, we have conducted total, laboratory-wide exercises simulating a major earthquake event. Emergency plans and procedures for communications, traffic control, and self-help, have all been tested. Simulated injuries requiring medical attention have also been included in these drills.

CLOSING STATEMENT

The ability of Lawrence Livermore National Laboratory to handle the aftereffects of a major earthquake has progressed a long way since January, 1980, when we gained a first-hand awareness of the potential destructiveness of a major seismic event. Considering the earthquake programs we have initiated, and our continued concern for the safety of our personnel and the surrounding community, we feel that LLNL is now much better prepared for earthquakes. The Lab is also committed to continually reviewing its positions, so as to maintain a high level of preparedness with respect to natural events such as earthquakes. A more detailed discussion of the Livermore earthquake and its impact upon LLNL, with accompanying tables, charts, and photographs, can be found in Reference 10.

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